



Quantification of Transient Changes of Thermospheric Neutral Density

Arthur Richmond
UNIVERSITY CORPORATION FOR ATMOSPHERIC RESEARCH

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Final Report

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Final Report

Quantification of Transient Changes of Thermospheric Neutral Density

PI: A.D. Richmond

Co-Is: L. Qian, Y. Deng

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Project Objectives

The project objective was to determine how the thermosphere responds to transient energy inputs, in order to improve the predictability of this response and its effects on satellite drag. Specific goals were to:

- Quantify how thermospheric density responds to transient Joule heating and solar-flare radiation;
- Reveal and understand the physical processes that determine the time delays, recovery times, and spatial variations of thermospheric density changes;
- Develop improved representations of Joule heating and solar-flare radiation absorption in the upper atmosphere for use in simulation models.

Work Carried Out and Results Obtained

1. Deng et al. (2013) used simulations with the Global Ionosphere-Thermosphere Model (GITM) to show that both Poynting flux and soft electron precipitation are important in producing neutral density enhancements near 400 km altitude in the cusp that have been observed by the Challenging Minisatellite Payload (CHAMP) satellite. Imposing a Poynting flux of 75 mW/m² in the cusp within the model increases the neutral density by 34%. The direct heating from 100 eV, 2 mW/m² soft electron precipitation produces only a 5% neutral density enhancement at 400 km. However, the associated enhanced ionization in the F-region from the electron precipitation leads to a neutral density enhancement of 24% through increased Joule heating. Thus, the net effect of the soft electron is close to 29%, and the combined influence of Poynting flux and soft particle precipitation causes a more than 50% increase in neutral density at 400 km, which is consistent with CHAMP observations in extreme cases. The effect of electron precipitation on the neutral density at 400 km decreases sharply with increasing characteristic energy such that 900 eV electrons have little effect on neutral density. Finally, the impact of 2 keV, 0.3 mW/m² proton precipitation on the neutral density is negligible due to a lowering of the altitude of Joule heating.

2. The altitudinal distribution of Joule heating is roughly proportional to the Pedersen conductivity at high latitudes. Based on Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) satellites observations from 2008 to 2011, Sheng et al. (2014) calculated the height-integrated Pedersen conductivities in both E (100-150 km) and F (150-600 km) regions and their ratio. The maximum ratio in the northern summer hemisphere is ~5.5, which is smaller than that from the Thermosphere-Ionosphere-Electrodynamics General Circulation Model (TIE-GCM v1.94) simulation (~9). This indicates that the energy inputs into the F region may be underestimated in the model. The seasonal variations of the ratio have been investigated for both hemispheres, and an interhemispheric asymmetry has been identified. The variational trend of the ratio is similar in both hemispheres, which reaches

minimum at local summer and maximum at local winter. However, the difference of the ratio from local summer to local winter in the southern hemisphere is larger than that in the northern hemisphere.

3. The wavelength dependence of solar flare enhancement is one of the important factors in determining how the Thermosphere-Ionosphere system responds to flares. Huang et al. (2014) ran the Flare Irradiance Spectral Model (FISM) for 61 X-class flares, and found clear wavelength dependencies, compared to pre-flare conditions. The influence of 6 different wavebands (0 - 14 nm, 14 - 25 nm, 25 - 105 nm, 105 - 120 nm, 121.56 nm, 122 - 175 nm) on the thermosphere was examined for the 2003 October 28 (X17.2-class) flare by coupling FISM with the National Center for Atmospheric Research (NCAR) Thermosphere-Ionosphere-Electrodynamics General Circulation Model (TIE-GCM). While the enhancement in the 0 - 14 nm waveband caused the largest enhancement of the globally integrated solar heating, the impact of solar irradiance enhancement on the thermosphere at 400 km is largest for the 25 - 105 nm waveband (EUV), which accounts for about 33 K of the total 45 K temperature enhancement, and ~7.4% of the total ~11.5% neutral density enhancement. The effect of 122 - 175 nm flare radiation on the thermosphere is rather small. The study also illustrates that the high-altitude thermospheric response to the flare radiation at 0 - 175 nm is almost a linear combination of the responses to the individual wavebands. The upper thermospheric temperature and density enhancements peaked 3 ~ 5 hours after the maximum flare radiation.

4. Cousins et al. (2013a) applied empirical orthogonal function (EOF) analysis, a variant of principle component analysis, to two years of plasma drift data from the Super Dual Auroral Radar Network radars in the mid-latitude to polar regions of the Northern Hemisphere. Using this technique, dominant modes of ionospheric electric field variability are identified and the spatial and temporal coherence of this variability is quantified. The first three dominant modes of variability, which, together with the mean, account for ~50% of the observed squared electric field, are characterized by global spatial scales and long time scales (on the order of 1 h). The first and second modes of variability represent the strengthening and weakening of the global convection pattern and the shaping of the convection pattern into asymmetrical round- and crescent-shaped convection cells. These two modes are well correlated with the Bz and By components of the interplanetary magnetic field. The third mode represents an expansion and contraction of the convection pattern, most notably on the dusk side, and is weakly correlated with the solar wind velocity. For EOFs beyond EOF 3, the power contained in the modes falls off rapidly, the characteristic spatial and temporal scales decrease, and generally weak correlations with external driving parameters are observed. These higher order EOFs likely capture more random behavior of the electric field variability. The notable exception to this trend is EOF 11, which captures mid-latitude variations on the dusk side and is enhanced during sub-auroral polarization stream events.

5. Cousins et al. (2013b) developed an assimilative mapping procedure to optimally combine information from Super Dual Auroral Radar Network (SuperDARN) plasma drift observations and a background statistical convection model to derive global distributions of electrostatic potential. This procedure takes into account statistical properties of the background model errors, obtained through the empirical orthogonal function analysis technique described above. The assimilative mapping procedure was evaluated quantitatively using cross-validation and was found to perform up to 43% better on average than the existing linear regression-based SuperDARN mapping procedure.

Furthermore, the mapped results from the assimilative procedure show a greater dynamic range in convection strength than do those of the regression-based procedure (i.e., the cross polar cap potential is smaller for weak driving conditions and larger for strong driving conditions). The application of the assimilative procedure is demonstrated for a case study containing a geomagnetic storm. It is shown that, qualitatively, the results of the assimilative procedure appear more smooth and consistent across both data-dense and data-sparse regions than do those of the regression-based procedure. The new procedure has been implemented for routine operation at the SuperDARN web site.

6. Kwak and Richmond (2014) analyzed the vertical component of vorticity and the horizontal divergence of the high-latitude neutral wind field in the lower thermosphere during the southern summer time for different interplanetary magnetic field (IMF) conditions with the aid of the NCAR Thermosphere Ionosphere Electrodynamics General Circulation Model, with the following results. (1) The mean neutral wind pattern in the high-latitude lower thermosphere is dominated by rotational flow, imparted primarily through the ion drag force, rather than by horizontally divergent flow. Poleward of -60 degrees magnetic latitude the magnitude of relative vertical vorticity often exceeds the magnitude of planetary vertical vorticity. (2) The vertical vorticity depends on the IMF. (3) The difference vertical vorticity, obtained by subtracting values with zero IMF from those with non-zero IMF, is much larger than the difference horizontal divergence for all IMF conditions. (4) The effects of IMF penetrate down to 106 km altitude. To determine the processes that are mainly responsible for causing strong rotational flow in the high-latitude lower thermospheric wind fields, a term analysis of the vorticity equation was also performed, with the following results. (1) The magnitude of forcing terms on vertical vorticity is significant poleward of -60 degrees magnetic latitude. (2) The primary forcing term that determines variations of the vertical vorticity is ion drag. This forcing is closely related to the flow of field-aligned current between the ionosphere and magnetosphere. Significant contributions to variations of the vorticity, however, can be made by the horizontal advection term. (3) The effects of the IMF on the ion drag forcing are seen down to around 105 km altitude. (4) The forcing of magnetic-zonal-mean By-dependent vertical vorticity by ion drag requires more than the 24 hours of these simulations to approach a steady state.

7. In work submitted for publication (T. Matsuo, D. Knipp, A. Richmond, L. Kilcommons, and B. Anderson, Inverse procedure for high-latitude ionospheric electrodynamics: analysis of satellite-borne magnetometer data) a comprehensive analysis of data from the magnetometers onboard the Defense Meteorological Satellite Program (DMSP) F-15, F-16, F-17 and F-18 satellites and the Iridium satellite constellation is presented, using an inverse procedure for high latitude ionospheric electrodynamics, for the period of May 29-30, 2010. The Iridium magnetometer data are from the Active Magnetosphere and Planetary Electrodynamics Response Experiment (AMPERE) program. The method of analysis is built upon the Assimilative Mapping of Ionospheric Electrodynamics procedure, but with a more complete treatment of the prior model uncertainty to facilitate an optimal inference of complete polar maps of electrodynamic variables from irregularly distributed observational data. The procedure can provide an objective measure of uncertainty associated with the analysis. The cross-validation analysis, in which the DMSP data are used as independent validation data sets, suggests that the procedure yields the spatial prediction of DMSP perturbation magnetic fields from AMPERE data alone with a median discrepancy of 30-50nT. Discrepancies larger than 100nT are seen in about 20% of total samples, whose location and magnitude are generally consistent

with the inherent discrepancy between DMSP and AMPERE data sets. Resulting field-aligned current (FAC) patterns exhibit more distinct spatial patterns without ringing artifacts in comparison to the FAC products provided by AMPERE. Maps of the toroidal magnetic potential and FAC estimated from both AMPERE and DMSP data under four distinctive Interplanetary magnetic field (IMF) conditions during a magnetic cloud event demonstrates the IMF control of high-latitude electrodynamics and the opportunity for future scientific investigation.

8. In work submitted for publication (Cousins, E.D.P., T. Matsuo, A.D. Richmond, and B.J. Anderson, Dominant modes of variability in large-scale Birkeland currents) properties of variability in large-scale Birkeland currents are investigated through empirical orthogonal function (EOF) analysis of one week of data from the Active Magnetosphere and Planetary Electrodynamics Response Experiment (AMPERE). Mean distributions and dominant modes of variability are identified for both the Northern and Southern hemispheres. Differences in the results from the two hemispheres are observed, which are attributed to seasonal differences in conductivity (the study period occurred near solstice). A universal mean and set of dominant modes of variability are obtained through combining the hemispheric results, and it is found that the mean and first three modes of variability (EOFs) account for 38% of the total observed squared magnetic perturbations (B2) from both hemispheres. The mean distribution represents a standard Region-1/Region-2 (R1/R2) morphology of currents and EOF 1 captures the strengthening/weakening of the average distribution and is well correlated with the north-south component of the interplanetary magnetic field (IMF). EOF 2 captures a mixture of effects including the expansion/contraction and rotation of the (R1/R2) currents; this mode correlates only weakly with possible external driving parameters. EOF 3 captures changes in the morphology of the currents in the dayside cusp region and is well correlated with the dawn-dusk component of the IMF. The higher-order EOFs capture more complex, smaller-scale variations in the Birkeland currents and appear generally uncorrelated with external driving parameters. The results of the EOF analysis described here are used for describing error covariance in a data assimilation procedure utilizing AMPERE data, as described in a companion paper.

9. In work submitted for publication (Cousins, E.D.P., T. Matsuo, and A.D. Richmond, Mapping high-latitude ionospheric electrodynamics with SuperDARN and AMPERE) an assimilative procedure for mapping high-latitude ionospheric electrodynamics is developed for use with plasma drift observations from the Super Dual Auroral Radar Network (SuperDARN) and magnetic perturbation observations from the Active Magnetosphere and Planetary Electrodynamics Response Experiment (AMPERE). This procedure incorporates the observations and their errors, as well as two background models and their error covariances (estimated through empirical orthogonal function analysis) to infer complete distributions of electrostatic potential and vector magnetic potential in the high-latitude ionosphere. The assimilative technique also enables objective error analysis of the results. Various methods of specifying height-integrated ionospheric conductivity, which is required by the procedure, are implemented and evaluated quantitatively. The benefits of using both SuperDARN and AMPERE data to solve for both electrostatic and vector magnetic potential, rather than using the data sets independently or solving for just electrostatic potential, are demonstrated. Specifically, solving for vector magnetic potential improves the specification of field-aligned currents (FACs), and using both data sets together improves the specification of features in regions lacking one type of data (SuperDARN or AMPERE). Additionally, using the data sets together results in a better correspondence between large-scale features in the

electrostatic potential distribution and those in the FAC distribution, as compared to using SuperDARN data alone to infer electrostatic potential and AMPERE data alone to infer FACs. Finally, the estimated uncertainty in the results decreases by typically ~20% when both data sets rather than just one are included.

10. Barbara Emery processed data from the Sondrestrom radar for 28-29 February 2008 to estimate vertical profiles of Joule heating, and compared them with results from TIEGCM simulations from 26 February to 04 March that used either Weimer [2005] or SuperDARN (<http://vt.superdarn.org/tiki-index.php?page=ASCIIData>) convection patterns as high-latitude inputs. The TIEGCM global height-integrated Joule heat was larger for the Weimer than for the SuperDARN convection patterns, because the Weimer patterns covered a larger area of the high-latitude region. The electric fields above Sondrestrom from both convection patterns were similar to the Sondrestrom observations for the eastward field, but neither was well matched with the observed northward field. Both runs missed the nighttime auroral enhancements seen in the radar data. DMSP F-13 passes over Sondrestrom near the cusp at the poleward edge of the aurora around 0930 MLT showed ~800 eV electron fluxes of ~4 mW/m² that ionize ~185km, where the estimated height-integrated Pedersen conductivity and Joule heat were similar to the radar estimates. When the simple Joule heat from the Pedersen conductance and the squared electric field was calculated with the MSIS model composition, the Sondrestrom estimates of the Joule heat per unit mass (W/kg) maximized just above the peak of the electron density, ~300km during the day and ~130km at night. The results were presented in a poster at the 2014 CEDAR Workshop (Emery, B., A. Richmond, A. Stromme, and J. M. Ruohoniemi, Sondrestrom Joule Heating Estimates, http://cedarweb.hao.ucar.edu/wiki/images/2/2b/2014CEDAR_POLA-04_Emery_2.pdf). Later work showed the percentage of the estimated height-integrated Joule heating (mW/m²) above 200km to be ~10% of the total during the day and ~2% during the night from the Sondrestrom radar in this period.

People Involved

Those receiving direct support from the funding were:

Art Richmond (PI)

Yue Deng (Co-I, University of Texas at Arlington)

Liying Qian (Co-I, NCAR/HAO)

Barbara Emery (NCAR/HAO)

Jose De La Garza (Graduate Student, U. Texas, Arlington)

Cheng Sheng (Graduate Student, U. Texas, Arlington)

Ben Foster (NCAR/HAO Software Engineer)

Collaborators:

Brian Anderson (Johns Hopkins U.)

P.C. Chamberlin (NASA Goddard SFC)

Ellen Cousins (NCAR/HAO)

Jeff Forbes (U. Colorado)

Tim Fuller-Rowell (U. Colorado)

Yanshi Huang (U. New Mexico)

Liam Kilcommons (U. Colorado)

Delores Knipp (U. Colorado)

Young-Sil Kwak (Korea Astronomy and Space Science Research Institute)

Ray Lopez (U. Texas, Arlington)
Tomoko Matsuo (U. Colorado)
Aaron Ridley (U. Michigan)
Ray Roble (NCAR/HAO)
Stan Solomon (NCAR/HAO)
Jeff Thayer (U. Colorado)
Xinan Yue (UCAR)
Z. Zhao (Peking U.)

Publications

Cousins, E.D.P., T. Matsuo, and A.D. Richmond (2013), Mesoscale and large-scale variability in high-latitude ionospheric convection: Dominant modes and spatial/temporal coherence, *J. Geophys. Res. Space Physics*, 118, 7895-7904, doi:10.1002/2013JA019319.

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